

Creating Capable Nanosatellites for Critical Space Missions

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In response to our U.S. government sponsors' needs for smaller spacecraft that will more effectively utilize access to space, APL has created a flexible and modular Multi-Mission Nanosatellite (MMN) spacecraft architecture that will allow low-cost execution of critical missions. As part of a pathfinder effort, an initial triple (three unit, or 3U) CubeSat hardware prototype is being designed to stow into a $10 \times 10 \times 34$ cm ($4 \times 4 \times 13.4$ in) containerized deployer. In this form factor, it will effectively capitalize on increasing secondary and tertiary launch opportunities by making use of unused volume and lift mass capability. To provide the desired combination of nanosatellite mission performance and reliability, APL developed an innovative approach using a multidepartmental team that leverages the technical insight and experience of the Laboratory's broad range of activities. This article presents the MMN motivation and approach, along with key design features of the initial 3U CubeSat configuration, currently being implemented in a fast development demonstration program and planned for launch in late 2011.

INTRODUCTION

Budgetary challenges and launch access limitations have historically constrained the ability to field new space capabilities and technologies for many U.S. government organizations focused on civil and national security alike. Throughout the past decade, advances in highly reliable commercial electronics, miniaturization techniques, and materials have enabled a new class of small nanosatellites, defined as having a total mass of 50 kg or less (according to the U.S. Air Force Univer-

sity Nanosat Program).¹ These nanosatellites now offer a solution to the problem of providing miniature, capable, and reliable satellites. While required aperture size and other instrument considerations often determine a minimum vehicle size, a nanosatellite provides an excellent, cost-effective means for conducting single-purpose missions. This niche of spacecraft design has historically been exercised by academia, whose principal focus has been on introducing the space systems engineering

process to students and providing some invaluable hands-on experience. Assuming launch could be arranged at all, attention to mission utility or on-orbit operations was generally a secondary consideration or an afterthought to the primary pedagogical goals.

The academic community has been very successful in developing, validating, and promulgating a secondary launch accommodation standard and the compatible spacecraft, the CubeSat. Originally conceived in the late 1990s by Bob Twiggs at Stanford University, the CubeSat was engendered by the prevalence of compact, affordable electronics and components that could be leveraged by students. The corresponding initial standard for a single-unit (1U) spacecraft was a nominal stowed volume of $10 \times 10 \times 10$ cm and mass of about 1 kg.² To facilitate the launch of these satellites as either a secondary payload with some measure of mission/orbit influence (and corresponding cost contribution), or more typically as truly “opportunistic” piggyback/tertiary accommodations, California Polytechnic State University developed the Poly Picosatellite Orbital Deployer (P-POD).³ Shown in Fig. 1a, the P-POD accommodates three CubeSats in an encapsulated linear configuration of individual satellites but also combinations of satellites occupying the same volume, including a single triple-unit CubeSat termed a “3U.” By using the entire dispenser, a 3U CubeSat can have a maximum length of approximately 34 cm and mass of 4.5 kg or more.² The first CubeSats were launched in 2000, with many more having been launched since then on myriad different launch vehicles. Through these launches, confidence was established such that CubeSats could be safely and readily incorporated into the launch vehicle and mission plan without impact to the primary payload. Growing global interest in launching nanosatellites, and continued design work, has advanced the availability of CubeSat launch access to multiple new vehicles [e.g., India’s Polar Satellite Launch Vehicle (PSLV)] and compatible adapters,⁴ which include the University of Toronto’s family of eXperimental Push Out Deployers (XPOD)⁵ and NASA Ames’s NanoSatellite Launch Adapter System (NLAS),⁶ which is shown in Fig. 1b. By developing standard, containerized deployer systems such as these and enforcing the associated CubeSat design, testing, and deployment requirements for manifest, the specific contents now become essentially irrelevant to the launch vehicle. This now enables a truly responsive flexibility by which payloads can be readily interchanged as a result of delivery issues, operational considerations, or needed mission capabilities.

Several of these deployers have also taken a forward-looking approach to enable accommodation of larger-sized nanosatellites; the XPOD in particular has already been used to deliver several non-U.S. spacecraft to orbit in the 10- to 20-kg range, with stowed cross-section dimensions of 20×20 cm and lengths of both 20 and

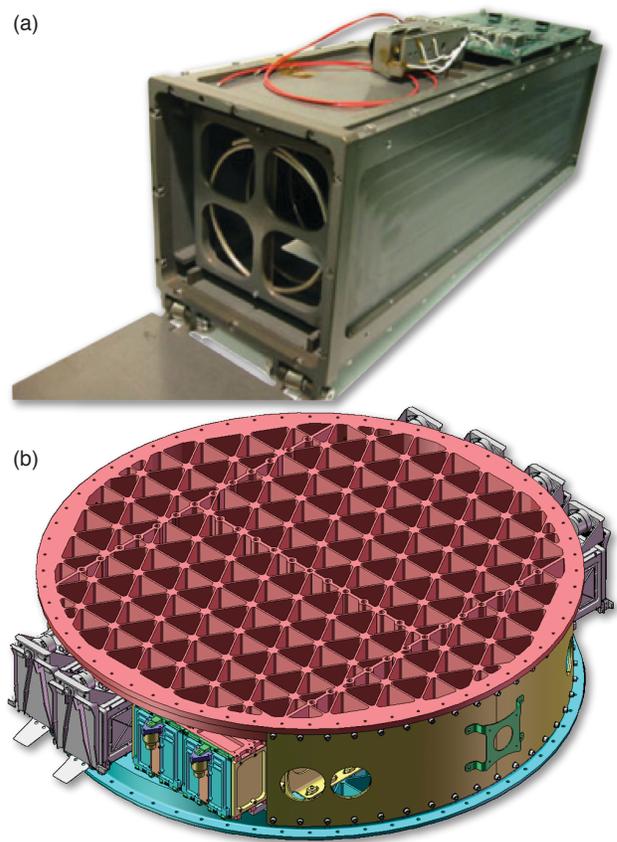


Figure 1. The P-POD is the foundational CubeSat-encapsulated deployment system capable of delivering any combination of three one-unit spacecraft (a). New reverse-compatible designs that permit larger nanosatellite secondary launch (courtesy of California Polytechnic State University, San Luis Obispo, <http://www.cubesat.org/>) include the NASA Ames’s NLAS (b), which can accommodate a total of 24U in single spacecraft increments as large as 6U.⁶

40 cm. The NLAS will accommodate up to four nanosatellites as large as $10 \times 22.6 \times 34$ cm (6U).⁶ These evolutions reflect the volumetric limitations of the CubeSat form factor, which due to its size can preclude the use of particular sensors and preferred components, or alternatively require potentially significant cost to miniaturize commercial off-the-shelf designs to fit. Arbitrarily breaking the CubeSat standard, however, is not the solution because the back-end launch premium to be paid for a custom manifest can be much greater than any savings to be realized through parts availability. Instead, 3U CubeSats can be utilized as pathfinders to larger nanosatellite designs that could also readily access secondary launch opportunities. Ongoing use and success of these larger but still standardized deployers will further progress toward the ultimate goal of truly serving critical missions with capability-commensurate, low-cost nanosatellite solutions.

MOTIVATION FOR THE MULTI-MISSION NANOSATELLITE ARCHITECTURE

As a consequence of the university-level successes with establishing secondary launch opportunities and demonstrating the potential for CubeSats, multiple government organizations, including NASA, the National Science Foundation, the National Reconnaissance Office, the Army Space Missile Defense Command, and the Air Force Space Missile Center, are now engaged in their own CubeSat programs, with varying science and technology objectives. Their focus has shifted from a learning exercise to executing meaningful missions that capitalize on the attractive low cost and comparatively short development schedule (typically 12–18 months) for CubeSats. APL has been active for the past several years, promoting novel nanosatellite-class solutions to sponsor mission needs in space weather^{7,8} and space situational awareness, in addition to several nanosatellite subsystem component development efforts. The Multi-Mission Nanosat (MMN) architecture was created after carefully considering the requirements and their implications for a broad set of high-priority missions; the intricate technical details associated with engineering a flexible, scalable platform; and the issue of quality management to ensure successful missions. Moreover, it was developed with the goal that it could become an open, nonproprietary standard broadly used by the developer community.

Through interactions with sponsors and industry, APL found an unserved need for a reliable, high-performance nanosatellite platform for critical space missions. Some low-cost space system approaches argue that if the system is made cheaply enough, its failure will not be a large financial setback. Although low cost is a valid concern, an approach without a high expectation of mission success undervalues the consequences of a failure to political capital with the sponsor, time and cost to rebuild and relaunch, and the loss of potentially critical mission capabilities. Capability and performance alone are not sufficient for a critical mission without a quality-assurance approach that provides confidence for success. When pragmatically employed from design inception, quality assurance and reliability can be achieved at a cost commensurate with the programmatic mission basis.

To enable development of low-cost nanosatellites for critical missions, APL undertook a rigorous internal effort to create a unique, specifically tailored Product Assurance Implementation Plan (PAIP) for nanosatellite missions using the MMN architecture. This PAIP was derived from the same APL quality management system that is applied to our most complex spacecraft and instrument programs, but reflects the balance between the cost of traditional processes and procedures and the essential elements that directly

contribute to mission success. The goal was to bring to bear the significant end-to-end experience and lessons learned from APL's more than 63 spacecraft programs and 150 flight instruments, distilling them down to processes and procedures suitable for use by a lean, fast-paced nanosatellite development effort. The nanosatellite PAIP, along with the other technical aspects of the MMN architecture, was created to be flexible to both mission and sponsor needs and is intentionally independent of implementation size, be it a 3U CubeSat or a 50-kg nanosatellite.

THE MMN CUBESAT PROTOTYPE

To validate the architecture, an initial 3U CubeSat prototype implementation is currently under development as part of the Multi-Mission Bus Demonstration (MBD) flight program. Referred to as the MMN-3U configuration, it provides a modular, high-performance, high-reliability platform for critical missions that can be served within the packaging limitations of the 3U CubeSat form factor. The spacecraft platform provides the power, three-axis pointing control, and data links necessary to flexibly accommodate different payloads and execute a broad set of missions. As shown in Fig. 2, when stowed, the system is fully compatible with the P-POD volume as well as with several others that are self-consistent with the standard.

The MMN architecture, and this 3U CubeSat implementation specifically, includes several key design features, described subsequently, which provide additional mission performance and operational flexibility.

Orbit Flexibility

Key to low launch cost for nanosatellites is acceptance of secondary manifest opportunities on a broad array of launch vehicles providing delivery to a wide range of low-Earth orbits. U.S. domestic options cur-

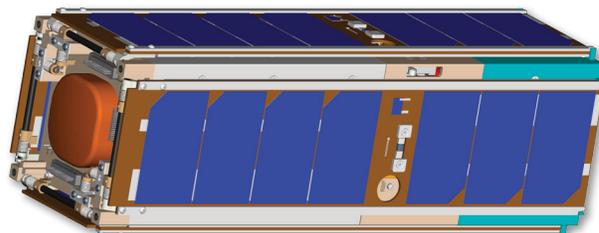


Figure 2. The MMN architecture has been initially implemented in a high-performance, high-reliability 3U CubeSat form factor suitable for critical missions. Shown here is the stowed configuration, with nominal payload accommodation volume shown in turquoise.

rently include the Orbital Minotaur I and IV, United Launch Alliance Atlas V Aft Bulkhead Carrier, Evolved Expendable Launch Vehicle Secondary Payload Accommodation, and the SpaceX Falcon 1e and Falcon 9. Other vehicles that will expand this list include the Lockheed Martin/ATK Athena II, Orbital Taurus II, and the SpaceX Dragon Trunk; the latter two are being developed in support of the NASA Commercial Orbit Transportation Services program. MMN's solar array and thermal control design approach is orbit agnostic, allowing fully functional mission operations across a broad range of orbits from 500- to 850-km altitude and 30° to 98.8° (sun synchronous) inclination. The following sections describe some of the technical details that enable this flexibility.

High-Power and Robust Thermal Management

For the majority of space missions, power is at a premium, and nanosatellites are no exception. Given the highly constrained packing volume, particularly in a P-POD-compatible CubeSat, a highly efficient combination of deployable solar arrays and power conversion and distribution electronics is essential. Equally critical and often overlooked in small spacecraft is thermal management and the rejection of heat generated by internal devices, particularly those operating at high (peak) powers, such as a radio transmitter. For the MMN solution, which has intentionally removed the dependencies on *a priori* mission knowledge, a point solution is not valid when orbital parameters, launch windows, and even preferred space vehicle operational orientation are not known.

In the MMN-3U configuration, a set of four double-sided, deployed solar arrays are oriented such that there is no spacecraft orientation in which energy generation is not possible. Across all sun-orbit beta angles, the system is capable of generating greater than 6 W of orbit average power. To maximize electric power transfer between the solar cell strings and the lower-voltage spacecraft power bus (battery), a peak-power-tracking power converter, developed particularly for nanosatellites, is used. Several DC-DC converters produce regulated bus voltages for use by the spacecraft and payload. A high-capacity lithium ion battery supports mission operations that require as much as 50 W peak power for durations up to 10 min per orbit, including during eclipse. Coupled with the high-peak-power capability, the thermal design can reject the heat, reflecting a detailed analysis of the conductive paths, radiated behaviors, and operational modes that drive thermal rejection performance. In the MMN-3U design, the spacecraft is cold biased, with thermal coatings used to configure the exact operating temperature range for a specific mission. Make-up heaters are also incorporated to protect critical components, such as the battery.

High-Performance Command and Data Handling

To provide scalable processing capability for the MMN command and data handling subsystem, a radiation-hard Aeroflex 32-bit LEON 3FT processor is used. This processor is central to a joint development effort serving several APL Earth-orbiting, lunar, and interplanetary missions, extending its application to nanosatellites. The LEON processor-based avionics, with its associated circuitry, is capable of extended operation under extremely stressing radiation, both total ionizing dose and single-event upsets and latchups, and environmental conditions.

The flight software can execute time-tagged commands uploaded from the ground, as well as complex command sequences, for spacecraft and payload operations. In addition to collecting, processing, and storing all spacecraft state of health, sensor measurements, and payload data, the flight software also formats and interprets data communications on the telemetry and command link, including associated Consultative Committee for Space Data Systems protocols, command extraction, and 128-bit (with option for 256-bit) Advanced Encryption Standard data encryption/decryption for all command and control links with the ground.

Electromagnetic Interference-Controlled Environment

Many missions require very low interference and noise levels within certain frequency bands. Spacecraft have many potential noise and interference sources, such as DC-DC converters, computer clocks, processor buses, and radios, which can create both narrowband and broadband interference. Including electromagnetic interference control measures in the spacecraft design from the beginning, such as component shielding, interface signal filtering, and other good design practices, is critical to avoiding costly corrective repairs during integration. The MMN structure has been designed as an integrated solution for electromagnetic interference shielding, thermal conduction, and radiation total ionizing dosage mitigation, with separate isolated cavities for bus and payload using five-sided "bathtubs" with labyrinth-seal covers, and filtered connectors for interfaces through the enclosure walls.

Mobile Antenna Ground Station

The MMN command and control approach can close the space-to-ground communications links with a simple, non-steering antenna, obviating the need for complex, high-gain antennas and positioners and enabling mobile operations in potentially disadvantaged conditions. As part of the prototype effort, APL is developing a portable ground terminal for spacecraft command and control and payload operations. The terminal bundles a communications transceiver into a

briefcase-sized, fully functional command console capable of task planning, contact scheduling, scripting, and orbit prediction for constellations. The design highly leverages a parallel development effort supporting the NASA Radiation Belt Storm Probes program, APL's Mission Independent Ground System, and joint product development effort between APL and L3 Communications. The ground software command and control solution has been baselined for all APL missions currently in development.

CURRENT STATUS AND GOING FORWARD

Continued progress is being made on MBD, the initial MMN-3U prototype implementation, as engineering and analysis activities continue into the critical design phase pursuant to a planned launch in 2011. The current deployed bus configuration is detailed in Fig. 3, which also shows the available payload volume. The modular design uses a flexible motherboard-daughterboard architecture, in which the individual printed wiring assemblies plug into a backplane. The backplane provides the board-to-board interconnects, eliminating much of the internal bus wiring harness. As part of its broader MMN architecture development and promulgation, APL is working closely with its suppliers and the developer community to define and codify

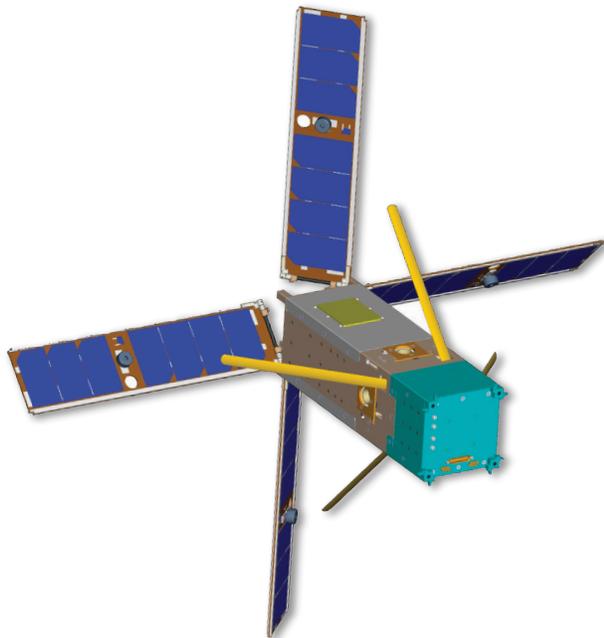


Figure 3. The modular MMN design architecture readily accommodates the spacecraft and payload elements needed for executing multiple different space missions within a 3U CubeSat form factor. Shown here is the deployed configuration with available payload volume in turquoise.

nonproprietary interface standards for subsystem components, payloads, and ground networks as they pertain to both CubeSats and larger nanosatellite systems. This effort is also serving as a catalyst for key technology development activities, by informing industry and academia of needed solutions that might be borne through their independent research and development and commercial endeavors, rather than through direct sponsor investment.

To support the quick-turn schedules of both the current and future nanosatellite flight programs, APL has established a dedicated, rapid-reaction nanosatellite development and testing facility. Located in a newly completed building on the APL campus, it provides 1600 square feet of access-controlled floor space for the concurrent development, integration, and testing of potentially multiple nanosatellite vehicles, depending on the size of the vehicles and environmental considerations. Appropriate engineering workstations and fabrication, assembly, and testing equipment have been installed in an electrostatic-discharge-controlled environment to facilitate efficient, cost-effective nanosatellite processing. APL also has the ability to build and test systems in classified environments, including secure compartmented information facilities, and is currently bringing online another 1600 square feet of cleared work area.

SUMMARY

APL is bringing its significant end-to-end experience with developing complex space missions to the emerging class of high-performance nanosatellites for critical missions. The MMN architecture enables a CubeSat platform that provides a yet-unrealized combination of performance and system reliability, enabling the rapid, cost-effective development of critical space missions. The modular, flexible design approach and key features incorporated into the nonproprietary MMN architecture and its initial CubeSat implementation address an unserved need of multiple sponsors for assured mission execution and performance. Working judiciously within the inherent constraints of nanosatellites and their standardized deployers, APL is now developing a new, disruptive capability for the nation.

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